National Aeronautics and Space Administration

Photonics on the Mission to Mars

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Agenda

- **Mission Overview**
  - Mission Trajectory
  - Launch Vehicle
  - Transfer Vehicle

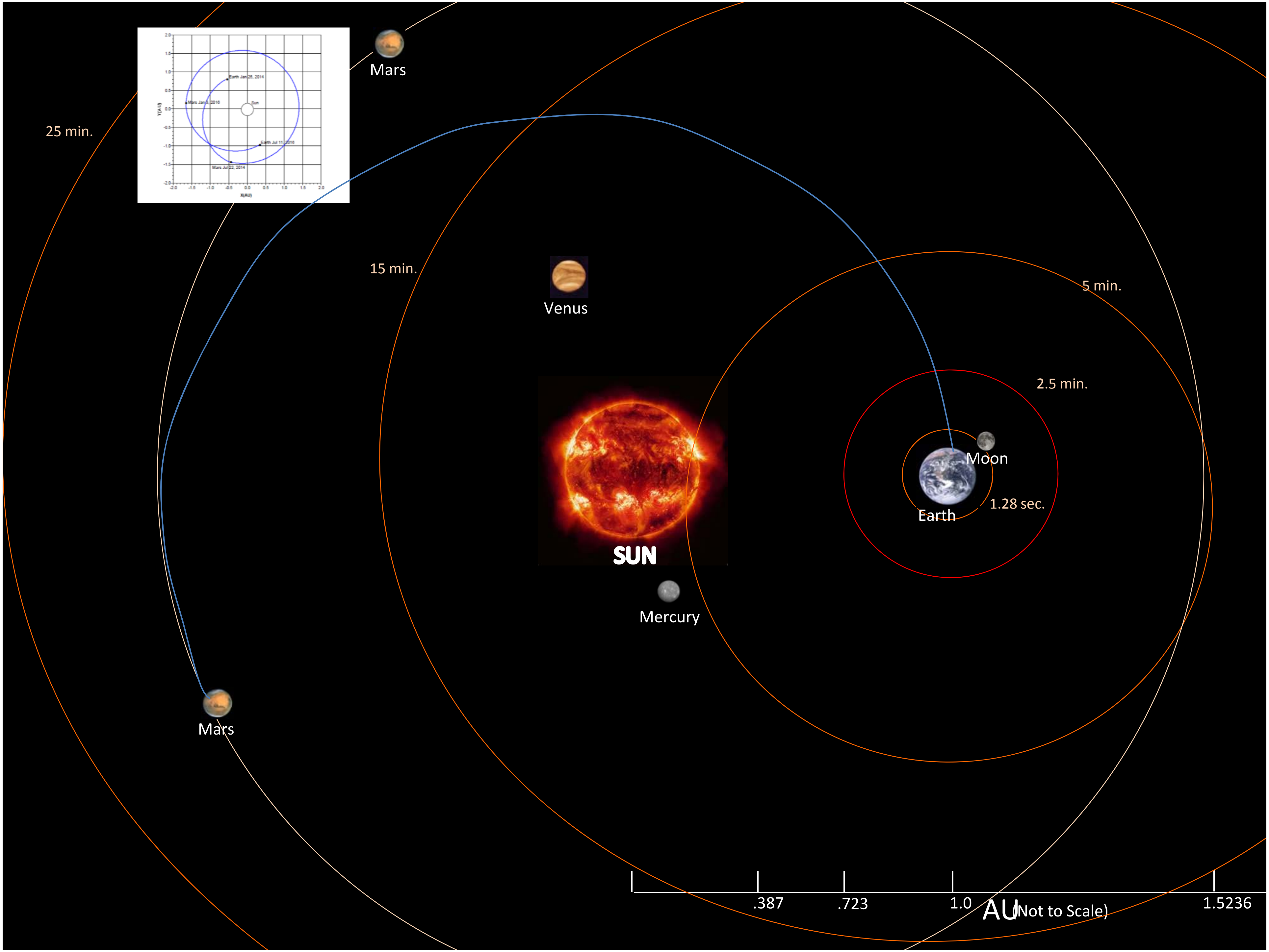
- **Mission Environments**
  - Launch Site
  - Earth Orbit
  - Interplanetary
  - Mars Orbit
  - Total Mission Exposures

- **Photonic Applications**
  - Optical Communications
    - Guided
    - Free Space
  - Optical Gyroscopes
  - LiDAR
  - Optical Sensing
    - Space Environment
    - Reactor Environment
  - Optical Coatings

Human Rated Space Flight Experience

Environment	ITV	Apollo	Shuttle Orbiter	ISS
Launch Site	6 months	6 months	30 years	6 months
LEO	18 months	2.5 hours	16 Days (EDO)	12.5 years
MEO	2 hours/2 hours	2 hours/2 hours	None	None
Interplanetary/Lunar	18 months	12.5 days	None	None
Martian Orbit	12 months	None	None	None

- **Human Rated Vehicles have more challenging Reliability and Maintenance requirements**
  - Must operate for the full duration of the mission without failure
  - Should require no scheduled maintenance in flight
    - Limited crew time for maintenance
    - Maintenance requires ease of access for repair or replace


Mars
25 min.
15 min.
Venus
5 min.
2.5 min.
Moon
1.28 sec.
Earth
SUN
Mercury
Mars
.387
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1.0
AU
(Not to Scale)
1.5236

Building on the U.S. Infrastructure

INITIAL CAPABILITY, 2017–21

Orion Multi-Purpose Crew Vehicle (MPCV)
- ***Lockheed Martin***

Launch Abort System

Interim Cryogenic Propulsion Stage
- Early flight certification for Orion
- Flexible for a range of payloads
- ***Boeing***

Core/Upper Stage
- Common design, materials, & manufacturing
- ***Boeing***

Avionics
- Builds on Ares software
- ***Boeing***

5-Segment Solid Rocket Boosters
- Upgrading Shuttle heritage hardware
- ***ATK***

Evolutionary Path to Future Capabilities
- **Minimizes unique configurations**
- **Allows incremental development**
- ***Advanced Development contracts awarded in Fiscal Year 2013 (FY13)***

EVOLVED CAPABILITY, Post-2021

Fairings (8.4 m or 10 m)
- Right-sized for the payload
- Received industry input in FY13

Upper Stage
- Commonality with Core Stage
- Optimized for Mission Capture

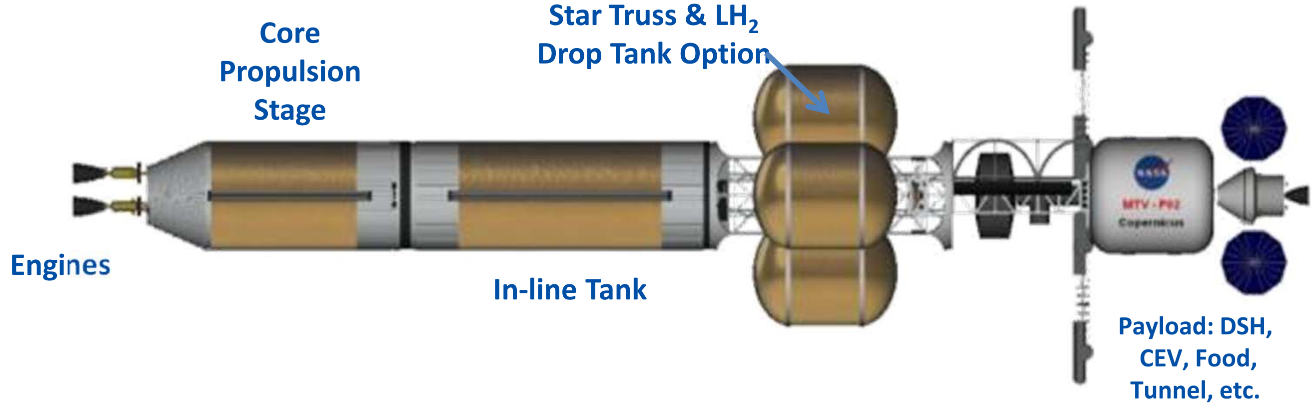
Advanced Boosters
- Competitive opportunities for affordable upgrades
- ***Risk-reduction contracts awarded in FY13***

RS-25

Core Stage Engines
- Using Space Shuttle Main Engine inventory assets
- Building on the U.S. state of the art in liquid oxygen/hydrogen
- ***Initial missions: Aerojet Rocketdyne***
- ***Future missions: Agency is determining acquisition strategy***

Working with Industry Partners to Develop America's Heavy-Lift Rocket

Notional Mars Transfer Mission -- 600 day Mars Piloted Stack



Transfer Vehicle Parameters:

- 8.9 m diameter

- Core Stage Length 17 m
- In-line Tank Length 20 m
- Drop Tank Length 14 m
- Truss Length 19 m
- Truss Length 12 m
- Deep Space Habitat Length 12 m

Vehicle Total Length 80 m

Mission Constraints / Parameters:

- 6 Crew

• Launch site time:	6 months (nom.)
• LEO assembly time:	18 months (nom.)
• Outbound time:	9 months(nom.)
• Stay time:	12 months (nom.)
• Return time:	9 months (nom.)
• Total mission time:	48 months (nom.)

Transfer Vehicle Description:

Transfer Vehicle consists of 3 elements:

1) core propulsion stage
2) In-line tank
3) Integrated star truss and dual drop tank assembly that connects the propulsion stack to the crewed payload element for Mars mission.

Each 100t element is delivered on an SLS LV to LEO. The core stage uses three engines. It also includes RCS, avionics, power, long-duration CFM hardware and AR&D capability. Interface structure includes fluid transfer, electrical, and communications lines.

Vehicle Environments

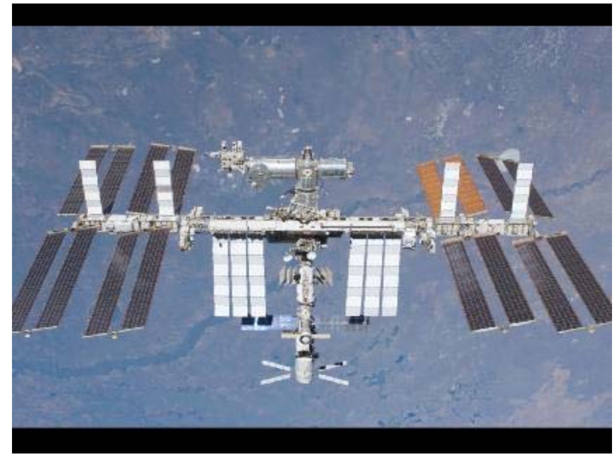
- **Oxygen**
  - Crew Cabin has a 20% O2/80% N2 environment
- **Thermal**
  - Conditioned Avionics Bay
    - -10 ºC to 80 ºC operating Range
  - Crew Cabin
    - 10 ºC to 40 ºC operating Range

Mission Environments

- **Launch Site Environment**
  - Tropical Environment
    - Humidity
      - 8% - 100% RH
    - Temperature
      - 0 °C – 50 °C operating range
    - High Salinity
- **Ascent Flight (US Commercial Launch Vehicle Ranges)**
  - Temperatures can approach 50° C – 95° C due to aero thermal heating
  - 130 -140 dB acoustic environment
  - 3000 – 7000 g shock environment

- **Space Environment**
  - Thermal
  - Ultra-Violet (UV)
  - Oxygen
  - Space Radiation
- **Space Environment varies greatly with proximity to Earth's atmosphere and the Van Allen Radiation Belt**
  - Low Earth Orbit (LEO)
  - Medium Earth Orbit (MEO)
  - Geosynchronous Earth Orbit (GEO)
  - Interplanetary Space is similar to GEO

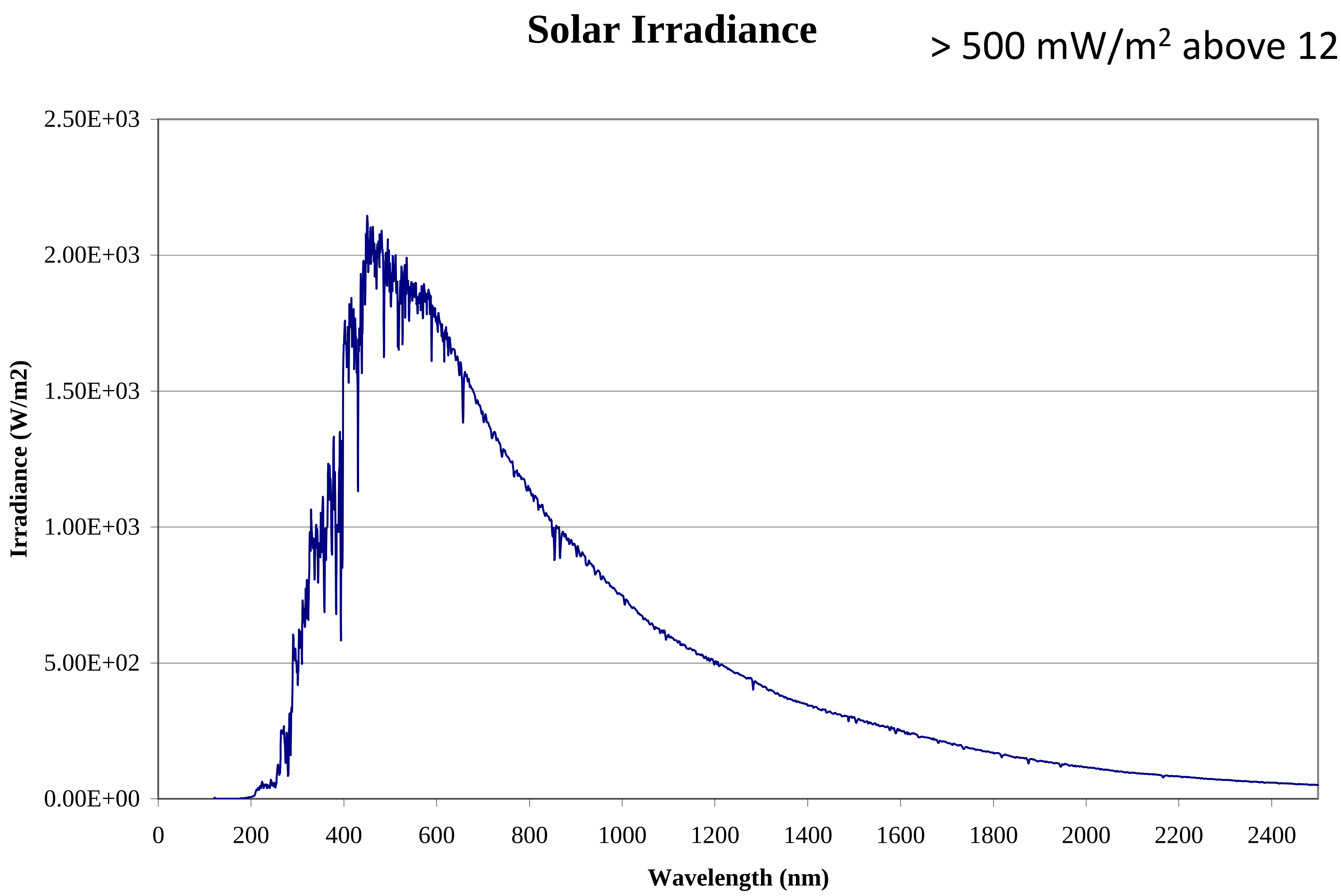
Assembly: Low Earth Orbit (LEO)



- **Oxygen**
  - Atomic Oxygen is a concern only within 600 km of Earth
  - 1021 atoms/cm2-year at 600 km altitude
- **Space Radiation**
  - 600 km circular orbit at 28.5 deg inclination
  - Electrons < 2 MeV dominate fluence
  - South Atlantic Anomaly is the greatest source of radiation fluence
    - Radiation flux closer to Earth due to shift in geomagnetic center from the Earth’s rotation
  - Galactic Cosmic Rays and Solar Protons contribute less to radiation environment than the electron and proton sources from the atmosphere
  - Shielding of 0.76 mm Al reduces dose to 1 krad annually
- **Thermal**
  - Varies significantly with spacecraft thermal sources and rotation rates
  - Approximately -50 ºC to 150ºC operating Range
- **Micro Meteorite/Orbital Debris (MMOD)**
  - Large distribution of tiny orbital debris impacting at high energies

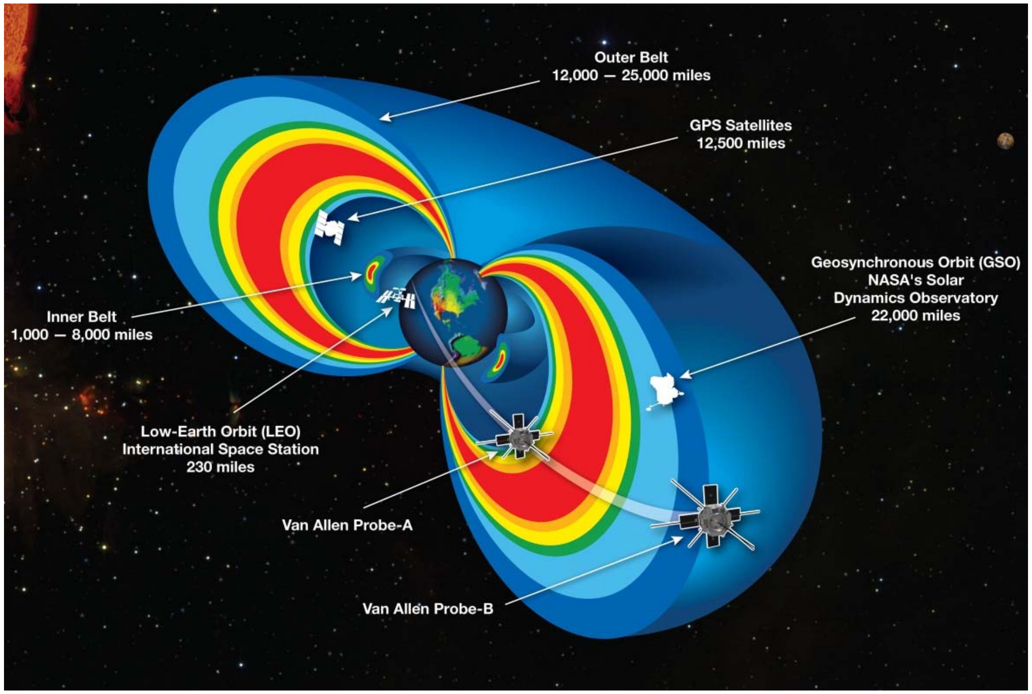
Ultra-Violet (UV) Radiation

> 500 mW/m^2 above 120 nm



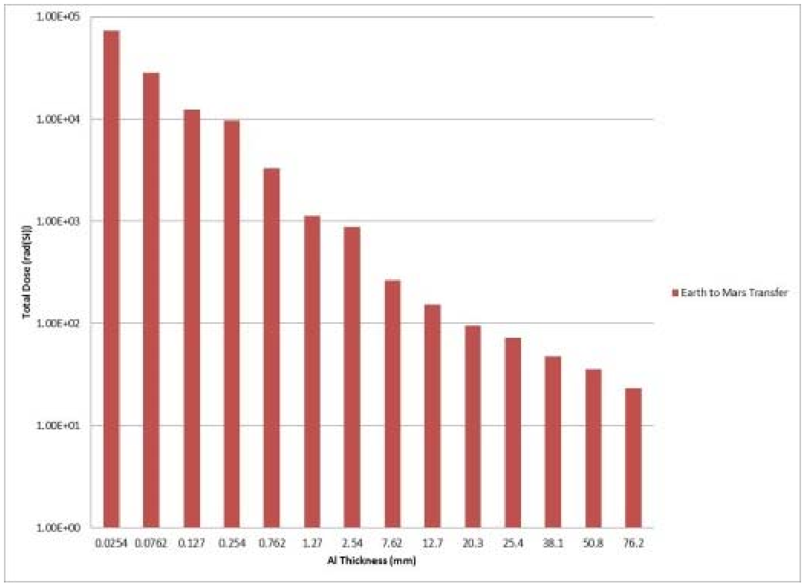
Medium Earth Orbit

- **Space Radiation**
  - 5000 km circular orbit, 0 deg inclination
  - Much greater electron and ion radiation due to the Van Allen radiation belt
  - 25.4 mm Al shielding reduces dose to 10 krad
  - 0.25 mm to 1.25 mm Al allows a total dose of 10 Mrad annually which leads to severe mechanical damage to electronics

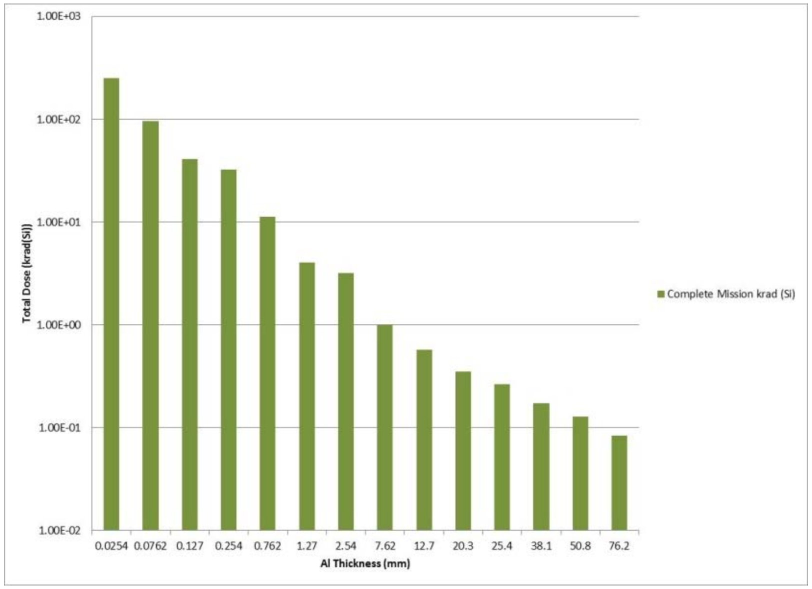


Interplanetary

- **Space Radiation**
  - Energetic electrons are most significant
  - Shielding of 5 - 10 mm reduces dose to ~1 krad (Si)
    - Energetic electrons dominate dose for Al shielding < 7.62 mm
  - Solar protons can dominate for Al shielding > 7.62 mm
    - Energies of 10 – 100 MeV
  - Solar Flares produce saturation events



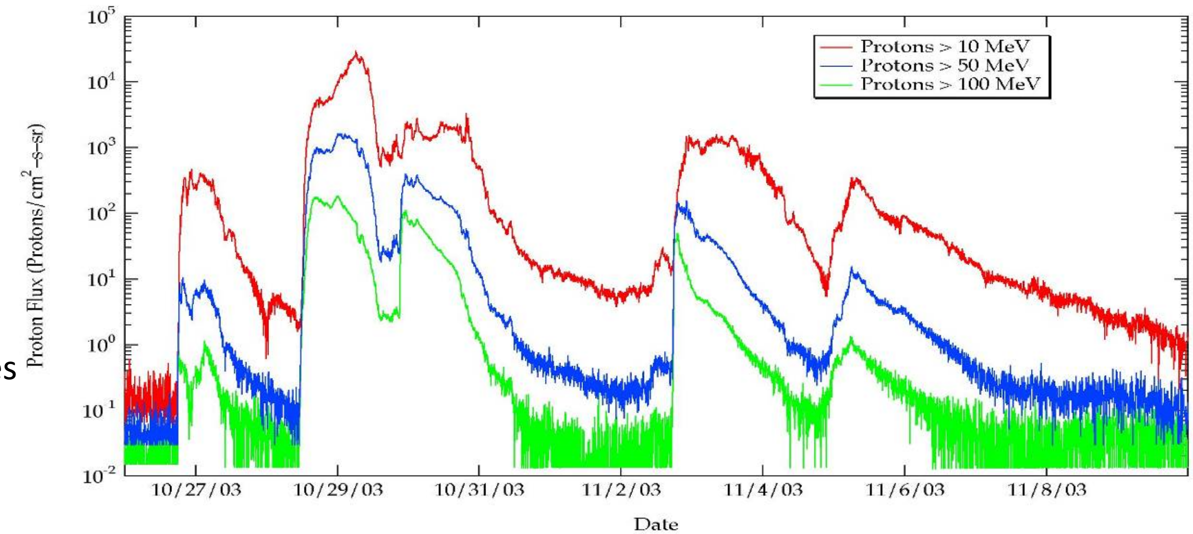
One Way Interplanetary Total Dose vs. Al Shielding

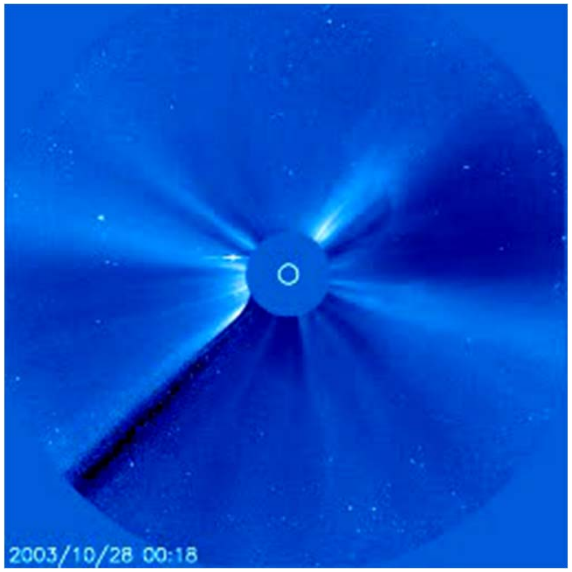


Total Radiation Dose from Earth Departure to Earth Return

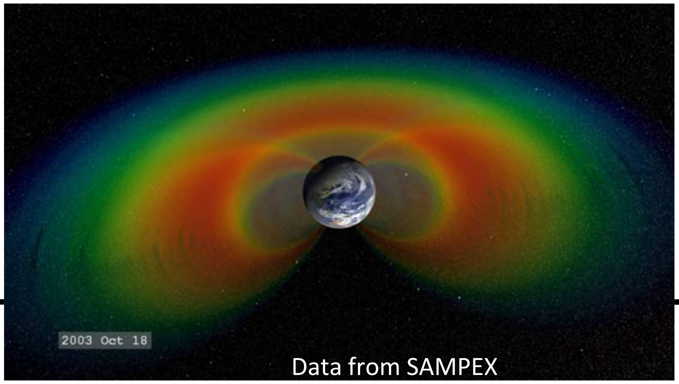
Solar Coronal Mass Ejection Event

- **In Oct-Nov of 2003, a series of X-class solar events occurred.**
  - High particle fluxes were noted.
  - Many spacecraft performed safing maneuvers.
  - Many systems experienced higher than normal (but correctable) data error rates.
  - Several spacecraft had anomalies causing spacecraft safing.
  - Increased noise seen in many instruments.
  - Atmospheric drag and heating issues noted.
  - Power grid systems affected,
  - Communication systems affected.
  - **Multiple Instrument FAILURES occurred.**
  - **Two spacecraft FAILURES occurred.**





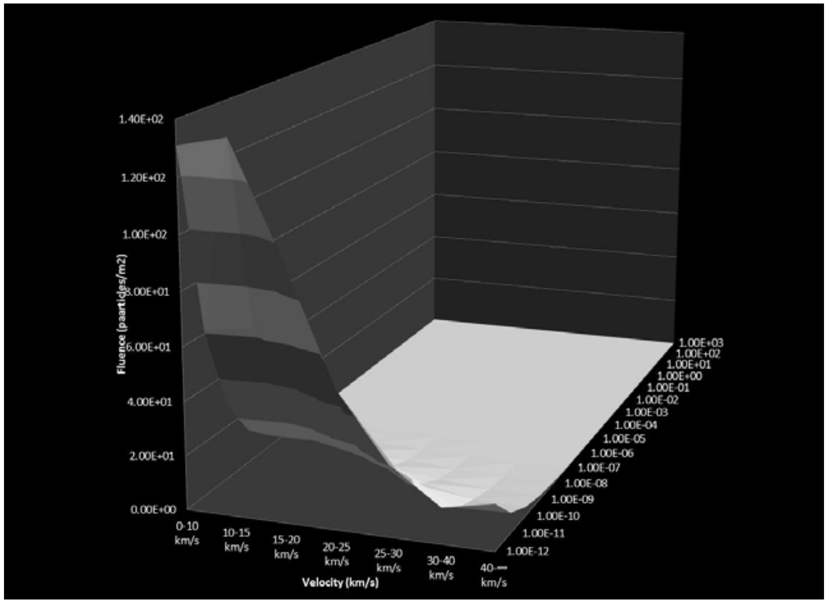
Video from Large Angle Spectrometric Coronagraph (LASCO)



Data from SAMPEX

Interplanetary

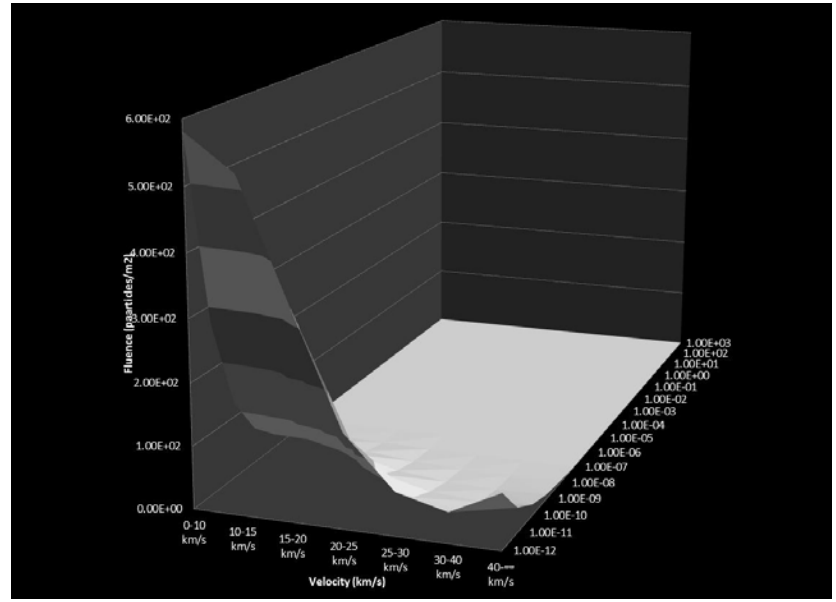
- **Meteorite Distribution**
  - Dominated by tiny particles (ng) with relatively low velocity
    - < 200 μJ impact energy
  - Impact concerns for particles > 1 μg for external structure
    - > 50 mJ impact energy



Interplanetary Meteorite Fluence Distribution

Mars Orbit

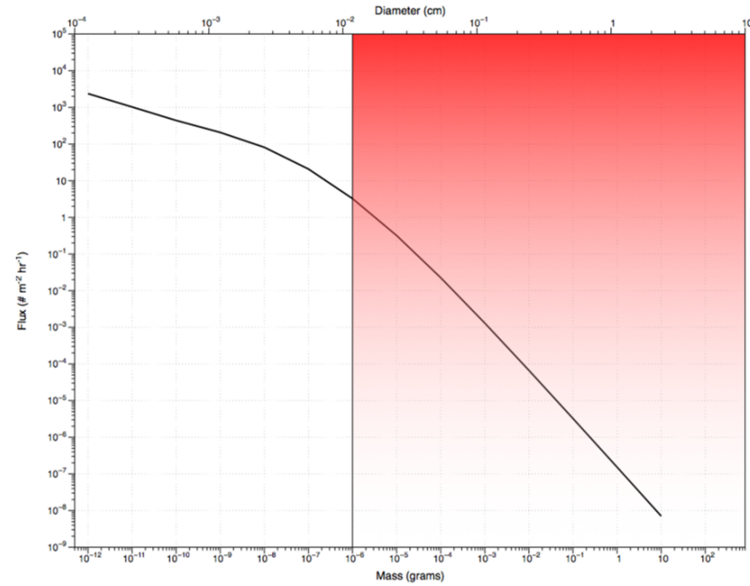
- **Oxygen**
  - Not a concern
- **Space Radiation**
  - Similar to interplanetary space
- **Thermal**
  - Varies significantly with spacecraft thermal sources and rotation rates
  - Approximately -50 ºC to 150ºC operating Range
- **Meteorite Distribution**
  - Dominated by tiny particles (ng) with relatively low velocity
    - < 200 μJ impact energy
  - Impact concerns for particles > 1 μg for external structure
    - > 50 mJ impact energy



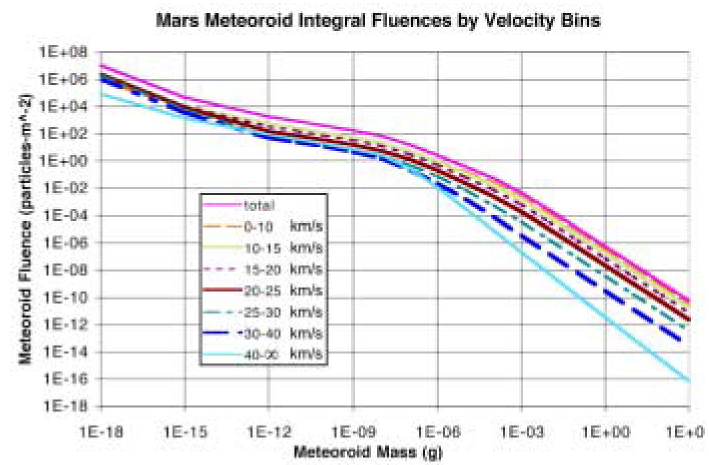
Meteorite Fluence

Total Mission

- **Tropical Environment at Launch Site**
- **Atomic Oxygen while in LEO**
  - 1021 atoms/cm2-year at 600 km altitude
- **Meteorite Distribution**
  - Dominated by tiny particles (ng) with relatively low velocity
    - < 200 µJ impact energy
  - Impact concerns for particles > 1 µg for external structure
    - > 50 mJ impact energy
- **Space Radiation**
  - 300 krad (Si) total exposure with no shielding
  - 15 krad (Si) total exposure with 0.762 mm Al Shielding
- **Thermal**
  - Varies significantly with spacecraft thermal sources and rotation rates
  - Approximately -50 ºC to 150ºC operating Range



Meteorite Flux from Earth Departure to Earth Return



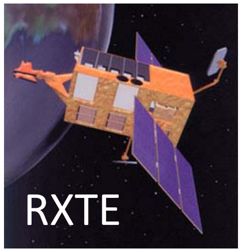
Photonics Applications

- **Optical Communications**
  - Guided
  - Free Space
- **Optical Gyroscopes**
- **LiDAR**
- **Optical Sensing**
  - Space Environment
  - Reactor Environment
- **Optical Coatings**

Photonics Applications

Optical Communications

- Much spaceflight experience with fiber optic communication networks
  - Fiber Distributed Data Interface (FDDI)
    - On board the International Space Station (ISS) since 2001
  - MIL-STD-1773
    - Small Explorer (SMEX)
    - NRL Microelectronics and Photonics Test Bed (MPTB)
    - Solar Anomalous Magnetospheric Panicle Explorer (SAMPEX)
    - Wilkinson Microwave Anisotropy Probe (WMAP)
    - Rossi X-Ray Timing Explorer (RXTE)
    - Hubble Space Telescope (HST) Solid State Recorder (SSR)
    - Boeing Photonics Space Experiment (PSE)
  - All fiber applications in the space environment depend on very careful control of fiber impurities
  - Need to consider longer cable distances

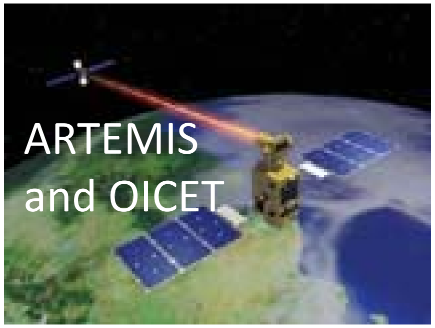


Reference	Device	Total Dose krad(Si)	Result	Source
Radiation-resistant erbium-doped-nanoparticles optical fiber for space applications	Erbium Doped Fiber Amplifier	40	Various loss depending on Al (worse) or Si content	gamma ray

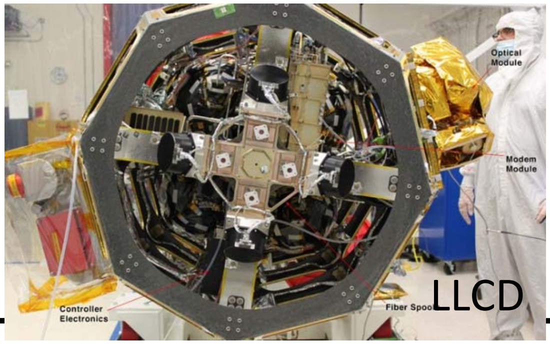
Photonics Applications

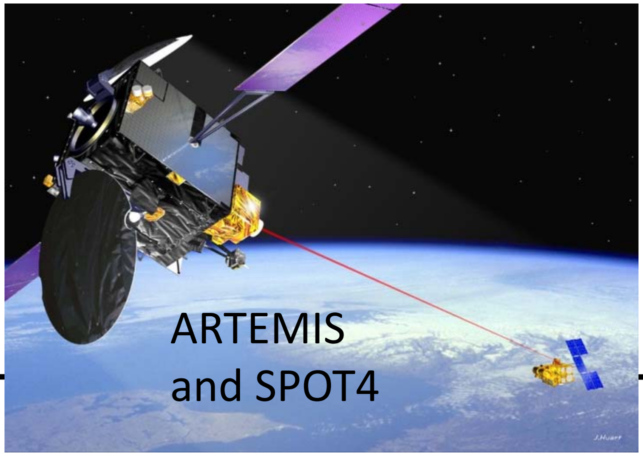
Optical Communications

- Free Space Optical Communications has been demonstrated in LEO
  - European Space Agency (ESA) demonstrated optical communications between
    - ARTEMIS and SPOT4
    - ARTEMIS to ground
    - ARTEMIS to an aircraft
  - ESA ARTEMIS and Japanese OICET satellite
  - Near Field Infrared Experiment (NFIRE) and the TerraSAR-X satellites



- Lunar Laser Communication Demonstration (LLCD) flying as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission demonstrating lunar distance communications





Photonics Applications

Optical Communications

- Interplanetary distances have not yet been demonstrated
  - Laser power levels
  - Tighter beam control
  - Receiver Telescopes

Reference	Device	Total Dose krad(Si)	Result	Source
RADIATION TESTING OF LIQUID CRYSTAL OPTICAL PHASE SHIFTERS FOR SPACE SURVIVABILITY	Liquid Crystal Optical Phased Array	2200	No EO degradation	gamma ray
		1.75	No EO degradation	neutrons
			Annealling (30-500 rad/s) did not produce degradation	
Radiation testing of liquid crystal optical devices for space laser communication	Liquid Crystal Optical Phased Array	2200	No EO degradation	gamma ray
		0.012545	increased insertion loss and switching time, while reducing Strehl	X-ray
Space qualification issues in acousto-optic and electro-optic devices	AOTF	788.6	-100 C operation, small degradation in AO polarization	proton
		1000	small changes in transmission and diffraction efficiency	gamma ray

Photonics Applications

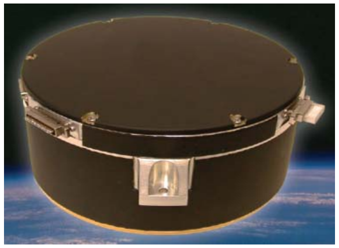
Optical Gyroscopes

- Spaceflight experience in LEO and planetary missions
  - LEO
    - International Space Station (ISS) Space Integrated Inertial Navigation System (INS)/Global Positioning System (GPS) (SIGI)
    - Proton TRS-500
    - Numerous Satellites

  - Planetary
    - Mars Rover LN-200S Fiber Optic Gyroscope (FOG)

Optolink
TRS-500
FOG

L3 Communications
RLGs



Honeywell
FOG

Photonics Applications

Optical Gyroscopes

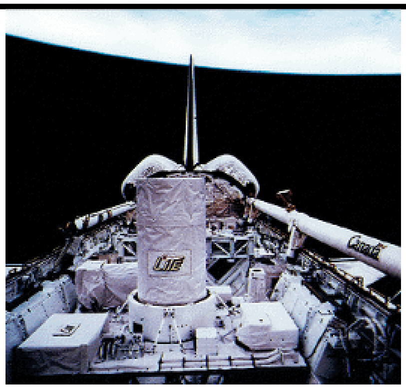
- Recent research on FOG radiation effects shows good operational performance
  - All components test well
  - Geometrical polarization
- High accuracy, low drift is important
  - Minimize ITV corrections, limiting control system sizing

Reference	Device	Total Dose krad(Si)	Result	Source
Research on two light sources design in fiber optic gyroscope for space application	FOG	20	PM fiber loss increased due to dopant color centers. Coupler and Detector had loss increases. Integrated Optics Chip not affected	Not specified
Research on the key techniques of fiber optic gyroscopes in the space application	FOG	50	PM fiber loss increased	Not specified
Radiation Effects on Opto-Electronic Devices for Fiber-Optic Gyroscopes	FOG	100	PM fiber loss increased due to dopant color centers in two fibers. A third PM fiber not affected indicating Geometrical birrefringence best. SLD, Coupler, Detector Integrated Optics Chip not affected.	gamma ray

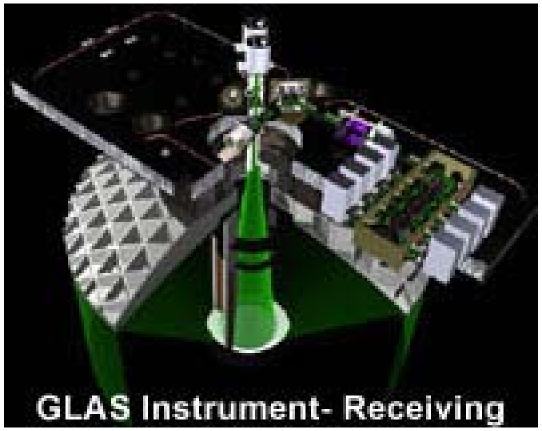
Photonics Applications

LiDAR

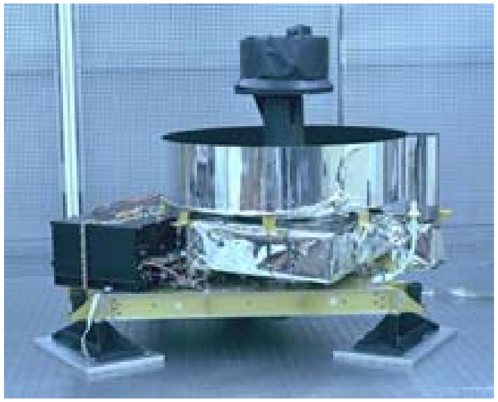
- Spaceflight experience in LEO and planetary missions
  - LEO
    - LiDAR In-space Technology Experiment (LITE)
    - Ice, Cloud, and land Elevation Satellite (ICESAT)
  - Planetary
    - Mars Global Surveyor (MGS) Mars Orbiter Laser altimeter (MOLA)
    - Mercury Surface, Space Environment, Geochemistry and Ranging (MESSENGER) probe



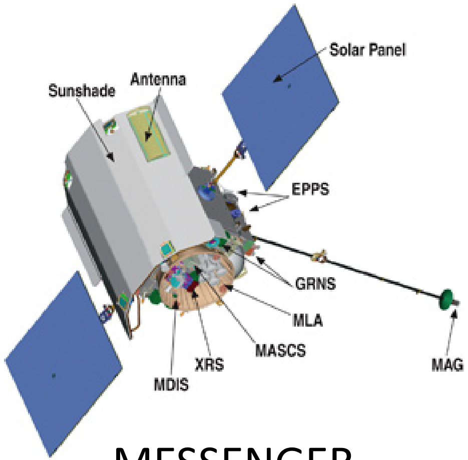
LITE



ICESAT



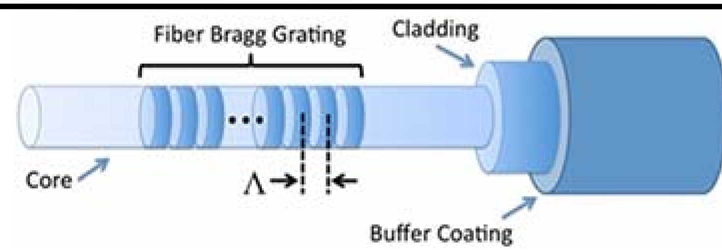
MGS MOLA



MESSENGER

Photonics Applications

- **Optical Sensing**
  - Optical Sensor Applications
    - Fiber Bragg Grating (FBG)
      - Temperature
      - Stress/Strain (Pressure)
    - Microbolometers
    - Chemical Sensing of Crew Environment
    - Radiation
    - Imaging
      - Infrared
      - Visible



National Instruments "**Fundamentals of FBG Optical Sensing**"

- Space Environment
  - Good thermal environment characteristics based on material selection
  - 300 krad (Si) total exposure with no shielding
  - 15 krad (Si) total exposure with 0.762 mm Al Shielding

Reference	Device	Energy MeV	Total Dose krad(Si)	Result	Source
Testing of Digital Micromirror Devices for Space-Based Applications	DMD	21	49	100% failure. Failure onset at 29 krad	proton
		34.5	43	100% failure. Failure onset at 31 krad	proton
		40.9	41	100% failure. Failure onset at 29 krad	proton
				173 K. No radiation. No errors.	

Photonics Applications

Reference	MATERIALS	VIABLE TEMP RANGE	COMMENT
Advanced end-to-end fiber optic sensing systems for demanding environments	Fibers		
	Slica	Close to 0 K to 1190°C when softening occurs - (Pure silica c n withstand to 1800°C)	Standard optical fiber material. Can withstand strains on the order of 1% in tension & 5 % compression.
	Sapphire	Melting point = 2040°C	Obtaining long lengths & adding claddings is challenging.
	PMMA	Low- 68 K to 400 K (127°C)	Have been reported to measure strains over 15%
	Coatings		
	Acrylate	-40°C to 85°C	Standard optical fiber coating
	Silicone	-40°C to 180°C	
	Polyimide	-190°C to 385°C	Most common temperature resistant coating
	Nitrides		Developmental
	Carbides		Developmental
	Gold	Melting point = 1040 °C	Most common hi-temp coating generally used up to 800°C. However gold is very soft and has been most successfully used in combination with nickel
	Nickel	Melting point = 1455 °C	Commonly used under gold coatings
	Platinum	Melting point = 1772 °C	Extreme hi-temp coating
	Tubing		
	Inconel	Melting point = 1372°C	
	Stainless Steel	Melting point = 1400°C to 1480°C depending on composition	
	Attachment		
	Epoxies	to 370°C	
	Ceramic Adhesives	to 1100°C	Can have problems when attaching to metals due to thermal expansion mismatch with metals
	Soldering		Promising method for attaching metal coated optical fibers to metals

Photonics Applications

- **Optical Sensing**
  - Reactor Applications
    - Communications
    - Fiber Bragg Grating (FBG)
      - Temperature
      - Stress/Strain (Pressure)
    - Extensometer (material elongation)
    - Photometer

Photonics Applications

Optical Sensing

- Reactor Environment
  - 35 Grad (Si) total dose over 4 years, 200 °C

Reference	Device	Temperature	Total Dose rad(Si)	Result	Source
Temperature monitoring of nuclear reactor cores with multiplexed fiber Bragg grating sensors	FBG	70 C	4.22M	23 day exposure, Small shift in FBG response	gamma rays and neutrons
Fibre Optic Extensometer for High Radiation and High Temperature Nuclear Applications	Fiber	150 C	1.60T	91 day exposure, optical loss increased. Able to compenstate for shifts.	gamma rays and neutrons
	Fiber	150 C	460G	27 day exposure, , optical loss increased. Some drift still unexplained.	gamma rays and neutrons
Radiation Testing of Optical Fibers for a Hot-Cell Photometer	Fiber	22 C	18.0M		gamma rays
Fiber-optic link components for maintenance tasks in thermonuclear fhsion environments	Fiber	200 C	1.34G	Pure SiO2 fiber had low losses	gamma rays and neutrons
	Si Detector	200 C	330M	Degraded quickly. One failed.	gamma rays and neutrons
	InGaAs Detector	200 C	330M	Quick and permanent degration	gamma rays and neutrons
	EEL	200 C	1.54G	Degraded with exposure time and increasing temperature. One failed.	gamma rays and neutrons
	VCSEL	200 C	1.34G	Degraded with exposure time and increasing temperature. Lens darkening.	gamma rays and neutrons

Photonics Applications

Optical Coatings

- Shows promise for protection of optical surfaces from contaminants
- Need to investigate resistance to abrasion from predicted particle impact energies
  - < 200 μJ impact energy

Reference	Device	Energy MeV	Total Dose krad(Si)	Result	Source
Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces	**polydimethylsiloxane (PDMS) polymers**	**63.8**	**148.6**		**protons**
	polydimethylsiloxane (PDMS) polymers		**152**		**gamma rays**
Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment	**Silicone**	**64**	**148.6**	**no degradation in outgassing**	**protons**
	Silicone	**64**	**148.6**	**No degradation over 8 years**	**protons**
	Silicone		**182.8**	**no degradation in outgassing**	**gamma rays**

Summary of Polymer Photonics Total Dose Testing

- **Polymers show promise for application in Space Environment**
  - Low adhesion shown to particles and moisture
  - Total dose testing generally below 1 Mrad (Si)
    - Some polymers showed degradation or shifts in performance
      - Needs to be compensated for in instrument design
      - Reliability needs to be considered
    - Some polymers showed improvements sustained for large total doses (> 300 krad (Si))
  - Abrasion resistance needs to be assessed for polymers used as optical coatings

Summary of Polymer Photonics Proton and Electron Total Dose Testing

Reference	Material	Energy MeV	Total Dose krad(Si)	Result	Source
Irradiation of hydrophobic coating materials by gamma-rays and protons: Space applications	dimethylsilicone (DMS) w 30% SMO	63.8	198.2	No statistical change in response	protons
Overview of photonic materials and components for application in space environments	Ge doped SI FBG	63	10000	Shift in optical power wavelength center and reflection	protons
	Mach Zehnder LD-3 polymer	64	600	EO Polylmer Degradation	protons
	DR-1/MA film	64	500	EO Polylmer Degradation	protons
	polyimide waveguide	64	600	EO Polylmer Degradation	protons
Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces	polydimethylsiloxane (PDMS) polymers	63.8	148.6		protons
Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment	Silicone	64	148.6	no degradation in outgassing	protons
Effect of Radiation on the Molecular and Contamination Properties of Silicone-Based Coatings	Silicone	64	148.6	No degradation over 8 years	protons
Space application requirements for organic avionics	CLD1/APC optical modulator	0.1	1000	12% increase in Vpi over 2 weeks after exposure	electrons
	TP7 optical modulator	0.1	1000	20% increase in Vpi over 2 weeks after exposure	electrons
An all-optical protocol to determine the molecular origin of radiation damage/enhancement in electro-optic polymeric materials	EO CPW1/APC modulator	25.6	100	Significantly improved Vpi	proton

Summary of Polymer Photonics Gamma Ray Total Dose Testing

Reference	Material	Energy MeV	Total Dose krad(Si)	Result	Source
Irradiation of hydrophobic coating materials by gamma-rays and protons: Space applications	dimethylsilicone (DMS) w 30% SMO	1.17&1.33	184.956	No statistical change in response	gamma rays
Overview of photonic materials and components for application in space environments	Mach Zehnder LD-3 polymer		4000	EO Polylmer Degradation	gamma rays
	polyimide waveguide		580	EO Polylmer Degradation	gamma rays
			5800	EO Polylmer Degradation	gamma rays
Effect of Ionizing Radiation on the Properties of Superhydrophobic Silicone Surfaces	polydimethylsiloxane (PDMS) polymers		152		gamma rays
Ultra Low Outgassing™ silicone performance in a simulated space ionizing radiation environment	Silicone		182.8	no degradation in outgassing	gamma rays
Overview of New and Emerging Radiation Resistant Materials for Space Environment Applications	Polymer w/ Fullerene on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	Polymer w/ DR1 on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	Polymer w/ NLS-1 on Siloxane	1.17&1.33	204.7	Improved Optical Transmission	gamma rays
	Polymer w/ SWCNT	1.17&1.33	175.4	No change (several day delay in post irradiation measurement)	gamma rays
	Polymer w/MWCNT	1.17&1.33	175.4	No change (several day delay in post irradiation measurement)	gamma rays
An all-optical protocol to determine the molecular origin of radiation damage/enhancement in electro-optic polymeric materials	CLD1/APC	1.17&1.33	208	No change in EO performance Thermal relaxation biggest effect	gamma rays
	CLD1/APC	1.17&1.33	428	No change in EO performance Thermal relaxation biggest effect	gamma rays
	CLD1/APC	1.17&1.33	850	No change in EO performance Thermal relaxation biggest effect	gamma rays
	EO CPW1/APC modulator		100	no change to improvement in Vpi	gamma rays
	EO CPW1/APC modulator (Dupont)		162	No change in 2, one degraded Vpi	gamma rays
	EO CPLD75/APC modulator		55	some degradation in Vpi	gamma rays

Photonics Applications

- **Key Considerations**
  - Thermal
    - Environments
      - 40 C – 80 C internal
      - 150 C external
      - 200 C internal reactor
    - Conductive Cooling
      - Must be minimized or eliminated to keep spacecraft radiators small
        - < 5 W for components
        - < 20 W for a packaged system
    - Radiative Cooling
      - If exposed to a cooler field of view
  - UV Exposure
    - Externally exposed devices must be protected

Photonics Applications

- **Key Considerations**
  - Abrasion Resistance (for exposed components)
    - Need to investigate resistance to abrasion from predicted particle impact energies
      - < 200 μJ impact energy
  - Radiation Effects
    - Space Environment
      - 300 krad (Si) total exposure with no shielding
      - 15 krad (Si) total exposure with 0.762 mm Al Shielding
    - Reactor Environment
      - 35 Grad (Si) total dose over 4 years